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## NEARLY STEADY FLOWS IN GONG PROTOTYPE DATA

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**ABSTRACT** Doppler velocity images obtained with the GONG prototype instrument were analyzed to measure the nearly steady photospheric flows. The data consist of 88 images each of velocity, intensity, and modulation obtained at 20:00 UT on 88 days from July 1992 to February 1994. Each velocity image was temporally filtered to remove the  $p$ -mode oscillations, masked to exclude active regions, and then analyzed using spherical harmonics and orthogonal functions as described by Hathaway (1992). The spectral coefficients show very consistent results for the entire time interval with some evidence of year-to-year variations. The rotation profile agrees well with previous results and exhibits a north-south asymmetry that reverses sign during the 20 month interval. The residual rotation velocities exhibit structures with amplitudes of  $\sim 5$  m/s that may be related to torsional oscillations. The meridional circulation is directed from the equator toward the poles with a peak velocity in the photosphere of  $\sim 50$  m/s. The higher order components are very weak but indicate a divergent flow from the mid-latitudes (opposite that found for the June 1989 data). The convective limb shift is well fit by a 3<sup>rd</sup> order polynomial. The convection spectrum has a prominent peak at spherical harmonic degrees of  $\ell \sim 150$  with very little signal in the low degree modes. Analysis of this signal shows that there is no evidence for giant cell convection at the level of  $\sim 10$  m/s for all modes up to  $\ell = 32$ .

INTRODUCTION

The GONG prototype instrument has been under development and testing for more than two years now and has acquired Doppler velocity data on well over 100 days. Much of this data is useful for studies of the nearly steady photospheric flows. The GONG Data Storage and Distribution System was queried for a listing of all time averaged images obtained at local noon (20:00 UT). The query showed 93 such images from July 1992 through February 1994. Three of these images were rejected due to flaws noted in a quick visual inspection. The remaining 90 images were passed through an analysis program described by Hathaway (1992) after which two more images were rejected due to spurious results. The output of this analysis program is a set of coefficients that fully describes the nearly steady flow components contained within each image. The results of the analysis are described in the following sections.

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## ROTATION RESULTS

The rotation profile for each velocity image is determined by calculating the rotation signal at each latitude and then fitting that signal with a series of Associated Legendre Polynomials,  $P_\ell^1(\cos \theta)$ , for  $1 \leq \ell \leq 8$ . The rotation velocity is then given by

$$V_\phi(\theta) = \sum_{\ell=1}^8 T_\ell^0 [\ell(\ell+1)]^{\frac{1}{2}} P_\ell^1(\cos \theta) \quad (1)$$

where the coefficients  $T_\ell^0$  then characterize the rotation profile. The  $\ell = 1$  term gives solid body rotation while the higher order terms give differential rotation. The odd terms give differential rotation symmetric about the equator while the even terms give the anti-symmetric component.

The average rotation profile is bracketed by those obtained by Howard and Harvey (1970) and Scherrer, Wilcox, and Svalgaard (1980). This agreement is in spite of the lack of any corrections for scattered light in the present analysis. On average all of the anti-symmetric components are vanishingly small. However, the  $\ell = 2$  term does show a linear trend over the 20 month period with the southern hemisphere rotating more rapidly in 1992 and the northern hemisphere rotating more rapidly in 1994. The most significant terms are the  $\ell = 1, 3$ , and 5 terms but even the  $\ell = 7$  term is significantly different from zero. Using the data from 1993 May 18 to 1993 June 28, comprising 33 images during which the instrument remained in the same configuration, gives

$$V_\phi(\theta) = (1965 - 265 \cos^2 \theta - 297 \cos^4 \theta) \sin \theta \text{ m/s}. \quad (2)$$

All other terms give contributions smaller than 5 m/s.

The residual rotation signal, obtained by removing the polynomial fit from the rotation signal, shows variations of about 5 m/s from latitude to latitude. Many of these jet-like features persist from day to day and are likely to be related to the torsional oscillations.

## MERIDIONAL CIRCULATION RESULTS

The meridional circulation signal is obtained after the rotation signal and limb shift signal have been removed from the data. The details of this procedure can be found in Hathaway (1992). Both the mathematics and the computational procedures have been extensively tested and found to work properly with a variety of different velocity signals. The data is projected onto spherical harmonics so that the meridional circulation is given by

$$V_\theta(\theta) = - \sum_{\ell=1}^8 S_\ell^0 [\ell(\ell+1)]^{\frac{1}{2}} P_\ell^1(\cos \theta). \quad (3)$$

The odd components represent anti-symmetric circulations with flow across the equator. The even components represent symmetric circulations. The  $\ell = 1$  term is particularly sensitive to north-south velocity gradients and is found to vary substantially in both sign and amplitude from day-to-day. For these reasons this term is neglected in the present study. All the other odd components are not significantly different from zero.

Among the even components the  $\ell = 2$  and  $\ell = 4$  are most significant. The  $\ell = 2$  component has an average value of  $22.8 \pm 1.0$  over the May-June 1993 period. This gives a circulation from the equator toward the poles with a peak velocity of 54 m/s at  $45^\circ$  latitude. The line-of-sight velocity due to this flow has a peak value of 41 m/s at  $\sim 55^\circ$  latitude. Although these numbers are about twice as high as most previously reported values, they cannot be attributed, at present, to errors in any of the analysis procedures. This signal persists in the data from day-to-day and only changes by a small amount from year-to-year.

The  $\ell = 4$  component has an average value of  $1.7 \pm 0.3$  over the May-June 1993 period. This gives a meridional flow that diverges from latitude bands centered at  $40.9^\circ$  north and south of the equator. This component does show a linear trend with values increasingly positive since late 1992. Analysis of data from 1989 gave a negative value for this component at that earlier time, Hathaway (1993).

### LIMB SHIFT RESULTS

The limb shift signal is obtained by finding the average velocity in annular rings about disk center with corrections for the presence of the meridional circulation signal. This signal is then fit with the shifted Legendre Polynomials so that the limb shift signal is given by

$$V_{LS}(\rho) = \sum_{n=0}^3 C_n P_n^*(1 - \cos \rho) \quad (4)$$

where  $\rho$  is the heliocentric angle from disk center. The zeroth order component just gives the average velocity of the Sun away from the observer. The higher order components give the structure of the convective limb shift and information about the underlying granulation. All three higher order terms are significant which might indicate the need for either higher order terms or a different dependent variable. All three coefficients show some indication of long term variations of a few percent. For the May-June 1993 period the average values give

$$V_{LS}(x) = -116x + 49x^2 + 656x^3 \text{ m/s} \quad (5)$$

where  $x = 1 - \cos \rho$ .

### CONVECTION RESULTS

The convection spectrum is obtained after removing the rotation, the meridional circulation, and limb shift signals from the data. The remaining cellular pattern is projected onto spherical harmonics. The sum of the amplitudes squared for each degree  $\ell$  gives a spectrum for the convection which is largely supergranulation for the resolution of the GONG instrument. The spectrum has a broad peak with a maximum at  $\ell \sim 150$ . It rises from zero at small  $\ell$  and shows no features with excess power to indicate the presence of giant cell convection. Images of the low  $\ell$  components including all modes up to  $\ell = 32$  have a peak-to-peak velocity range of  $\sim 10$  m/s. This signal does not, however, appear to be due to convection. The center-to-limb variation is more representative of radial flows than horizontal flows and the features do not persist from day to day. While this

indicates that giant cells must have amplitudes in the photosphere smaller than  $\sim 10$  m/s, further work must be done to determine the source of this signal.

One puzzling aspect of the convection spectrum is how it differs from the spectrum obtained with Cacciani's Na Magneto-Optical Filter at Mt. Wilson, Hathaway *et al.* (1991). With the Na resonance filter the convection spectrum peaked at  $\ell \sim 100$ . Although that spectrum contained considerable noise at small wavenumbers it still showed a rise in power from  $\ell \sim 30$  to the peak. This substantial difference in size for the supergranulation may be due to the different atmospheric levels probed by the two instruments. The GONG line is a photospheric line while the Na D lines are formed in the lower chromosphere.

## CONCLUSIONS

This analysis of data from the GONG prototype instrument shows consistent results for the various components of the nearly steady flows in spite of continuing changes to the instrument itself. The analysis suggests that solar cycle variations in the differential rotation and meridional circulation should be addressed by data obtained with the GONG instruments. The analysis also points the way to additional work with the present data. The amplitude of the meridional circulation signal remains as a major concern. Possible sources of this signal include problems with the velocity calibration and the polynomial fit to the limb shift signal. Work in these areas is in progress.

An additional surprise in the analysis is the difference in the convection spectrum between the GONG data and the Mt. Wilson MOF data. The source of this difference may reveal information about the height dependence of the convective velocities.

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